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A Case Study of Potential Causes of Frost Heave

Karen S. Henry

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PREFACE

This report was prepared by Karen S. Henry, Research Civil Engineer, Civil and Geotechnical Engineering Research Branch, Experimental Engineering Division, of the U. S. Army Cold Regions Research and Engineering Laboratory, at Northwestern University under the sponsorship of the Federal Aviation Administration and the U.S. Army Corps of Engineers. USACE funding was provided by DA Project, *Operations and Maintenance, Army, Facilities Investigation Studies*, 722894.M7, *Construction Support Work Studies*; Work Unit, *Use of Geotechnical Fabrics to Minimize Seasonal Frost Effects.*

The following people contributed to this research effort: Dr. Charles Dowding, Dr. Barbara Ann-G. Lewis and Dr. Jorg O. Osterberg of Northwestern University, Evanston, Illinois; Dr. Richard Berg, Dr. Patrick Black, Edwin Chamberlain, Richard Roberts, Jonathan Ingersoll, Rosanne Stoops, Matthew Pacillo, Edward Perkins, William Bates and Jacqueline Castor of CRREL.

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A Case Study of Potential Causes of Frost Heave

KAREN S. HENRY

INTRODUCTION

Frost action in frost-susceptible soils can significantly degrade the performance of highway and airport pavements, causing differential heaving and buckling of pavements during winter periods as well as softening of entire pavement sections during spring thaw. These effects can result in pavement cracking and failures such as potholes and pumping of saturated fine-grained soils through the cracks with the passing of traffic. Furthermore, differential frost heaving in the winter may lead to rough pavement and hazardous travel conditions.

This research investigates the possible causes of frost heave at Ravalli County Airport in Hamilton, Montana, by determining the frost-susceptibilities and hydraulic properties of soil at the airport. Ravalli County Airport has severe differential frost heave problems each winter; in the winter of 1984–85, 610 m (2000 ft) of runway was closed because of unsafe conditions caused by frost heaving. This field study focused on the three necessary conditions for frost heave to occur—1) frost-susceptible soil, 2) available water and 3) freezing temperatures.

Several parameters were monitored during the fall and winter of 1985–86. These included depth to water table, soil moisture tension and soil temperature at various depths as well as depth of frost penetration. Additionally, elevation differences due to frost heave were measured by survey at the time most likely for maximum frost heave.

GENERAL SITE INFORMATION

Ravalli County Airport is located in southwestern Montana on the eastern edge of the city of Hamilton (Fig. 1). Hamilton is located in the eastern portion of the Bitterroot River valley in a physiographic region known as the Bitterroot Valley area.

The Bitterroot Valley area is an intermountain valley that is bordered by the Bitterroot Mountains on the west and the more gently sloping foothills of the Saphire Mountains on the east. The physiographic subdivisions of the area include 1) flood plains, 2) fan-terraces of the side creeks, 3) Pleistocene fans, benches and moraines of the west side and 4) high Tertiary benches of the east side. The entire valley floor is underlain by thick alluvial deposits.

Ravalli County Airport is in a relatively flat area (slopes of 1–3°) of low alluvial fans and flood plains formed by creeks feeding the Bitterroot River. Soils of the region are derived from "weakly stratified silty fine earth" of the uplands (Tertiary benches) to the east of the area (USDA 1959).

The airport has severe differential frost heave problems each winter, especially near the southern end of the runway and the center portion of the taxiway. Figure 2 is a site map of the airport. As mentioned earlier, during the winter of 1984–85, the airport was forced to close 610 m (2000 ft) of the runway. The problem heave areas are consistently between survey stations 41+00 and 46+00 on the runway and 30+00 and 38+00 on the taxiway. The differential heave at the airport occurs where there is overall a large amount of heaving.

During the fall and winter of 1985–86, several parameters that pertain to the frost heaving process were monitored at Ravalli County Airport by airport personnel. These field data are analyzed here and are contained in an earlier report (Henry 1987).

All monitoring stations correspond to locations where soil borings were taken, so that there is an accurate record of soil types at each station. Moni-

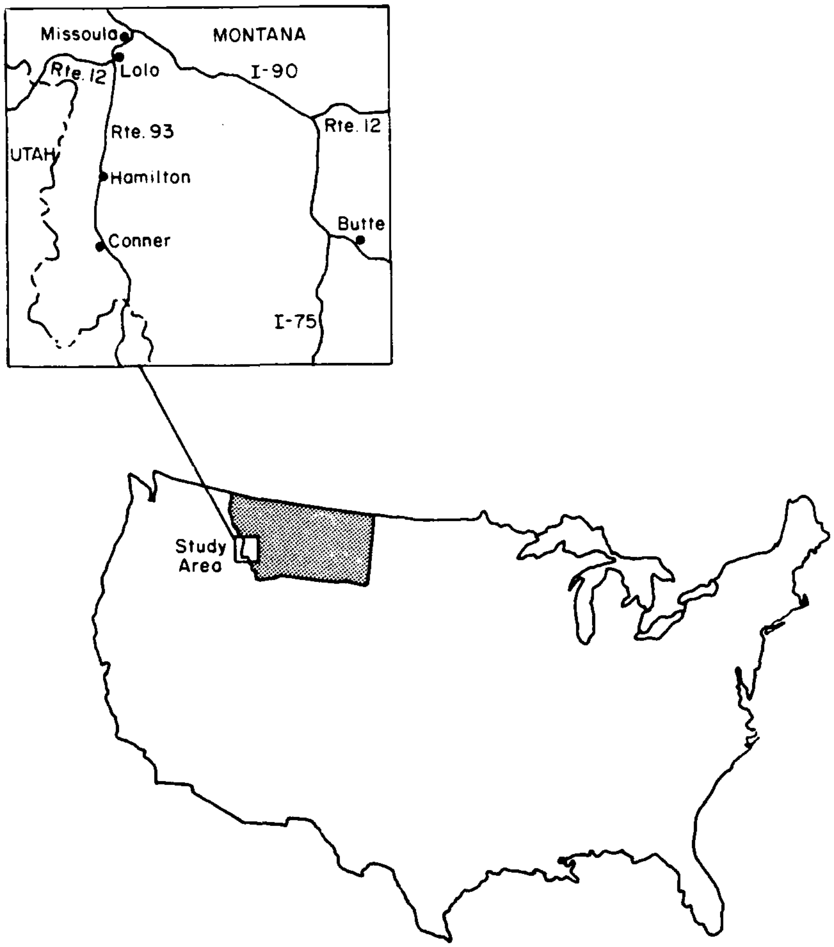


Figure 1. Location map of Hamilton, Montana.

toring efforts centered on runway survey stations 26+00 and 43+50 (monitoring stations 3 and 6, respectively, on Fig. 2) because they are respectively located in low-heaving and high-heaving areas.

Depth to water table was monitored at all seven stations, five of which were on the runway and two on the taxiway (Fig. 2). Frost penetration was measured at three stations and soil moisture tension and soil temperature at various depths were measured at two sites. Table 1 and Figure 2 may be used to coordinate locations with the parameters monitored.

A baseline elevation survey was conducted on 4 September 1985 along both the runway and the taxiway. Another survey was made on 16 January 1986 at the time when maximum heave was thought to take place. A third survey was conducted on 12 March 1986 after the ground had thawed.

Figure 3 contains graphs of frost heave on 16 January 1986 as well as cross-sections prepared from boring logs. The graphs present elevation increases as opposed to absolute elevations. The accuracy of elevation measurement is plus or minus 0.6 cm (0.02 ft), and a heave difference of 2.5 cm in 15.2 m (1 in. in 50 ft) is considered unacceptable for pavement surfaces.*

The minimum heave recorded was 0.9 cm (0.4 in.) at 30+00 on the taxiway centerline. The maximum heave recorded was 16.5 cm (6.5 in.) at 30+25 on the taxiway, 4.6 m (15 ft) to the right of the centerline. These two points lie very close to each other and dramatize the differential heave problem at the airport. On the runway, there was a minimum of 1.5 cm (0.6 in.) of heave at 26+25, 4.6 m (15 ft) to the right of the centerline. The maximum heave of 13.7 cm (5.4 in.) was recorded at 46+00 on the centerline.

*Personal communication with R. Berg, CRREL, 1986.

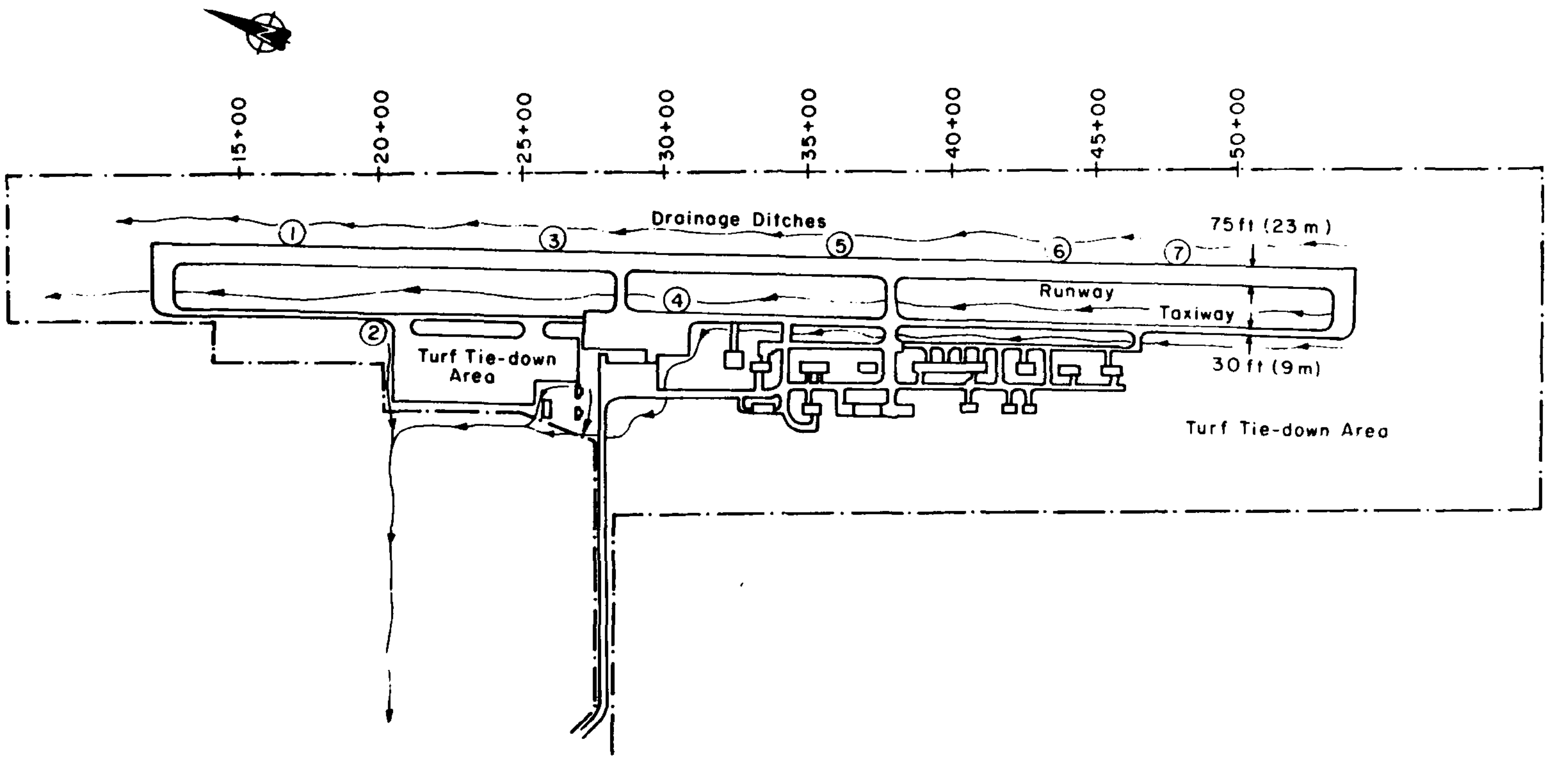
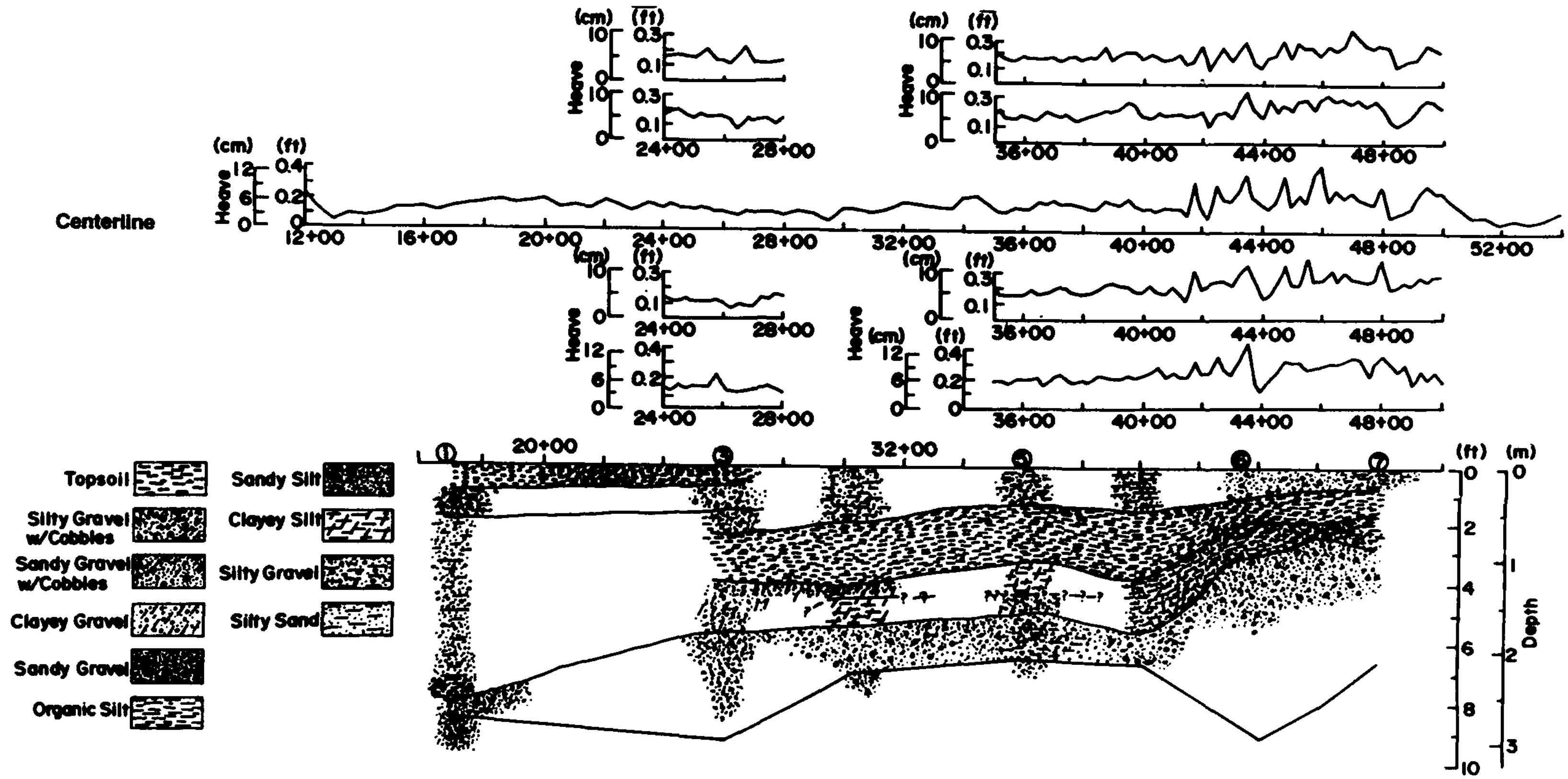
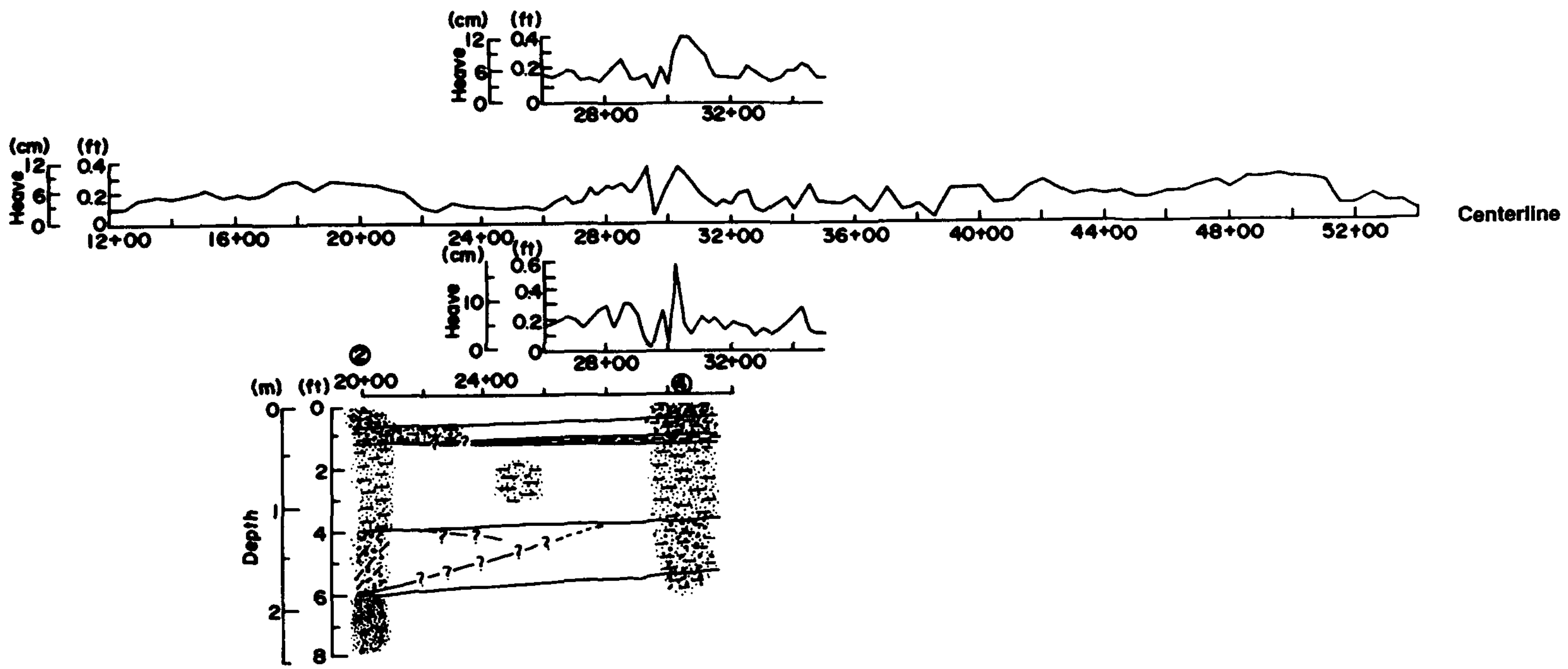


Figure 2. Site map of Ravalli County Airport (circled numbers indicate monitoring stations).



a. Runway (upper graphs are profiles taken 9.1 and 4.6 m [15 and 30 ft] to the right [bottom set] and left [upper set] of the centerline).

Figure 3. Frost heave on 16 January 1986 and soil cross section prepared from profile logs.



b. Taxiway (upper graphs are profiles taken 4.6 m [15 ft] to the right [bottom graph] and left [top graph] of the centerline).

Figure 3 (cont'd).

Table 1. Survey stations and parameters monitored.

Station number	*Survey station*	*Parameters monitored*
1	17+00, 12 m (40 ft) left of centerline, runway	Depth to water, depth of frost.
2	20+00, 6 m (20 ft) right of centerline, taxiway	Depth to water.
3	26+00, 12 m (40 ft) left of centerline, runway	Depth to water, soil moisture tension with depth, soil temperature with depth.
4	30+50, 6 m (20 ft) left of centerline, taxiway	Depth to water, depth of frost.
5	36+00, 12 m (40 ft) right of centerline, runway	Depth to water.
6	43+50, 12 m (40 ft) left of centerline, runway	Depth to water, depth of frost, soil moisture tension with depth, soil temperature with depth.
7	48+00, 12 m (40 ft) left of centerline, runway	Depth to water.

In the remainder of this report, data will be presented and examined that deal with the three necessary factors for frost heave to occur—1) frost-susceptible soil, 2) water supply and 3) freezing temperatures. Additionally, the data gathered throughout the season will be presented and analyzed in an attempt to determine why there are differences in the amounts of frost heave among different areas at the airport.

SOIL TYPE AND VARIABILITY

General soil information

As most alluvial soils are variable in composition, reflecting ranges in parent material and energy of depositional environment, one would expect soils at Ravalli County Airport to be variable yet reflect the silty nature of the parent material. The soils on which the airport is located are of the Corvallis Series, which typically have a silt or loam layer grading from moderately thick surface soils to weakly stratified silt loam and loam at depths ranging from 30.5 to 51 cm (12 to 20 in.) (USDA 1959). The loamy soil is underlain by sands and gravels at depths varying from 1 to 1.5 m (3 to 5 ft.). The soils are further described by the USDA (1959) as being moderately permeable, having a high moisture holding capacity, and being poorly drained because of a high water table. They are calcareous throughout, although they contain no zones of lime accumulation.

The surface soils at the airport include four variants of the Corvallis silt loam—1) slightly saline, 2) poorly drained, 3) moderately saline and 4) moderately shallow, slightly saline (USDA 1959). The slightly saline variant is noted as being slightly to moderately saline with mostly sodium salts. Moderately shallow, slightly saline refers only to the fact that sand and gravel occur at the relatively shallow depths of 51 to 91 cm (20 to 36 in.). The moderately saline Corvallis silt loam is referred to as being moderately to strongly saline and poorly drained, and the poorly drained variant cannot be cultivated unless artificially drained.

It is important to note that the surface soils at the site probably vary from those shown on the USDA (1959) survey because of the construction of the airport. Fill may have been imported and the surface soils relocated, mixed and compacted. In addition, surface drainage has been constructed, which has likely lowered the salinity through leaching of sodium.

It is noted that the Corvallis Series surface soils have a "frost action potential" defined as high, and a "shrink–swell potential" defined as low by the USDA (1972). The restriction of the use of these soils for road, street and parking area construction is classified as "severe" owing to frost action potential (USDA 1972). The naturally occurring water table ranges from 31 to 61 cm (1 to 2 ft) below the surface.

In summary, a preliminary study of the soils of the Ravalli County Airport area provides clear indication of potentially severe frost heaving.

Soil classification and frost susceptibility

The runway, built in 1963, is described in a site-visit report as consisting of 2.5 cm (1 in.) of asphaltic concrete over an 46-cm (18-in.) gravel base (Vinson 1985). In 1983, a taxiway was constructed with a 23-cm (9-in.) aggregate base course over the natural subgrade, which was compacted to a depth of 15 cm (6 in.) (Vinson 1985). Little is known about the amount of cutting and filling that was done during the construction periods; however, it was probably minor owing to the flatness of the site. A 1981 soils boring log indicates that 61 cm (2 ft) of fill was probably brought in on the extreme northern end of the runway.

Three sets of boring log soil profiles are available for the airport. One set was completed in 1981 in

connection with an investigation prior to the 1983 taxiway construction. Since these profiles were taken 23 m (74 ft) and 43 m (140 ft) off of the edge of the runway, they probably are the closest record of "natural" soil conditions at the site. A second set of boring logs was supplied with a 1985 report on the causes of frost heaving at the airport by Braun Engineering Testing of Montana, Inc., to the Ravalli County Commissioners, and was taken in March 1985. The third set of logs was prepared by GMT Consultants, Inc., in August of 1985 as reconnaissance work for the winter of 1985–86 data gathering. In the GMT survey, eight profiles were obtained along the runway and two on the taxiway. The boring logs prepared by GMT Consultants, Inc., are contained in Appendix A.

Examination of the runway cross section reveals that the soils at the airport are indeed quite variable. It appears that the entire cross section is composed of frost-susceptible soils (i.e., silty) to depths that are likely to freeze (about 1 m or 3–4 ft). The available information does not show any sections of the runway as being more frost-susceptible than the rest, except, perhaps, for a general trend towards more fine-grained soils at the extreme northern end of the runway (survey station 17+00), the end that has relatively low heave. Soil boring logs also show that the base course material used throughout the entire airport, and which has been called "gravel" in previous engineering reports, contains enough fines to be considered frost-susceptible and in some locations is classified accord-

Table 2. Grain size distribution and Unified Soil Classification of soils at Ravalli County Airport. (Analyzed by both GMT Consultants, Inc., and USACRREL.)

Depth (ft)	Depth (cm)	% Grain size passing 4 (4.76 mm)	% Grain size passing 40 (0.42 mm)	% Grain size passing 200 (0.074 mm)	Percent finer than 0.02 mm	Cu	United Soil Classification
Station 3							
0.2–2.0 (CRREL)	6–61	53.1	32.5	19.6	12.3	601.9	GM, Brown Gravel Sand
2.2–3.8 (GMT)	67–116	100	95	75	50	35	MH, Dark Gray Organic Silt
2.6–4.8 (CRREL)	79–146	89.8	84.4	67.3	43.1	23.3	ML, Black Gravel Silt
3.8–5.5 (GMT)	79–146	NR	NR	39.4	NR	—	GC, Medium Greenish Tan
4.8–5.1 (CRREL)	146–174	58.2	36.8	17.0	8.5	—	GM, Red Gravel Sand
Station 6							
0.17–0.5 (CRREL)	5–15	69.4	21.7	9.7	5.7	41	SM, Tan Gravel Sand
0.5–1.0 (CRREL)	15–25	56.1	30.2	7.1	4.1	53	SM, Brown Gravel Sand
1.0–1.8 (GMT)	25–55	100	93	71.8	38	37	ML, Dark Grayish Brown Silt
1.6–2.0 (CRREL)	49–61	99.2	95.3	69.3	35.7	20	ML, Gray Gravel Silt
1.8–3.0 (GMT)	55–91	96	91	64.1	64	33	ML, Light Greenish Tan
2.7 (CRREL)	82	99.2	96.6	61.5	21.8	10	ML, Tan Silt

Table 3. Frost-susceptibility determinations of soils from Ravalli County Airport by various criteria.

Depth (ft)	Depth (cm)	Casagrande (% finer than 0.02 mm)	USACE (Berg and Johnson 1983)	Standard USACRREL frost heave test lab determination: Comparison with other soils	Standard USACRREL frost heave test lab determination: Actual tests (Heave rate, mm/day)
			Station 3		
0.2–2.0	6–61	FS	F2	M–H	VL (0.48)
2.2–3.8	67–116	FS	F4	H–VH	—
2.6–4.8	79–146	FS	F4	VH	M–H (3.84)
4.8–5.1	146–174	FS	F1	T	—
			Station 6		
0.17–0.5	15–25	FS	S2	M	VL (0.56)
0.5–1.0	15–25	FS	S2	L	L (1.63)
1.0–1.8	25–55	FS	F4	VH	—
1.6–2.0	49–61	FS	F4	VH	M–H (3.60)
2.7	82	FS	F4	L,L–M	H (4.12)
1.8–30	5591	FS	F4	VH	—

Standard CRREL frost heave test frost susceptibility classification abbreviations:
H = High L = low M = medium T = trace VH = very high VL = very low

ing to the Unified Classification System as silty sand.

Soil samples were collected at survey stations 26+00 and 43+50 (monitoring stations 3 and 6 respectively) and sent to CRREL to have soil grain size distribution and laboratory frost-susceptibility determined. GMT, Inc., also determined grain size distribution curves for soils collected at these stations. Table 2 shows the results of both CRREL's and GMT's grain size analysis, and the resulting classifications according to the Unified Soil Classification System. Appendix A contains the grain size distribution curves.

Table 3 presents frost-susceptibility determinations of the soils at stations 3 and 6 according to four systems—1) Casagrande's criterion, 2) U.S. Army Corps of Engineers system, 3) comparison with laboratory frost-susceptibility tests on similar soils and 4) actual laboratory frost-susceptibility determinations. A companion report (Henry, in press) gives information on the Casagrande and USACE frost-susceptibility classification systems.

All soils at stations 3 and 6 are classified as frost-susceptible according to the Casagrande criterion. If the quantity of soil finer than 0.02 mm is considered as an indication of relative frost-susceptibility, station 3 soils appear to be more frost-susceptible than soils collected from station 6. However, the U.S. Army Corps of Engineers classification indicates no significant differences in susceptibility to frost action between stations 3 and 6.

In an attempt to more closely define the frost-susceptibility of soils, short of the actual laboratory determination, soil type (Unified Soil Classification System) and grain size distribution of the soils collected at stations 3 and 6 were compared to soils tested previously in CRREL standard frost heave tests. Berg and Johnson (1983) present results of laboratory frost-susceptibility determinations on many soils; frost-susceptibility classifications for

the closest matches were assigned to the samples from Ravalli County Airport. Matches were based on Unified Soil Classification, percent finer than 0.02 mm and the coefficient of uniformity (*Cu*). This comparison shows no significant differences in the frost-susceptibility of soils between stations 3 and 6.

Finally, Table 3 also presents actual laboratory frost-susceptibility determinations for soils collected at Ravalli County Airport, based on the standard CRREL frost heave test (see Henry [in press] for test details). The heave rates for a constant rate of frost penetration of 12.7 mm/day (0.5 in./day), on which the frost-susceptibility classification is based, are also listed.

A comparison of the last two columns in Table 3 shows that the results of laboratory determinations of frost-susceptibility are sometimes significantly different from those of laboratory frost-susceptibility determination on "similar" soils. This emphasizes the empiricism of our current working knowledge of the frost-susceptibility of soils. It is also clear that for all practical purposes there are no differences in frost-susceptibility classifications between soils at stations 3 and 6.

Frost heave and soil type

Study of Figure 3a reveals that the high heaving area near the southern end of the runway (represented by station 6) has a shallower layer of sandy gravel than the rest. The relatively high heaving area begins where this layer of gravel starts to become shallow. The depth to the silt/gravel interface ranges between 76 and 168 cm (2.5 and 5.5 ft) beneath the heaving area—gradually increasing in depth towards the north end of the runway. The gravel layer also contains higher amounts of clay towards the north, except for the extreme northern end.

For the taxiway soil profile, in consideration of the frost heave information, the silt-sand/gravel interface occurs at 116 cm (3.8 ft) under station 4, a high heaving area. A low heaving area, represented by station 2, is underlain by clayey gravel at a depth of 122 cm (4.0 ft).

To determine whether the hydraulic conductivity of the subgrade soils might be a limiting factor in ice segregation at Ravalli County Airport, I estimated the rate of water transport required to sustain the observed frost heave. The rate of heave was calculated by taking the heave of an area and dividing by the time elapsed between 12 November and 16 January (65 days). This time interval was chosen because 12 November was the latest date that no frost penetration was measured, yet there

Table 4. Estimates of required flow rates to sustain frost heave for two sections at Ravalli County Airport.

Runway section	*Average heave (ft)*	*(cm)*	*Required water flow rate (cm/s)*
Survey stations 41+00 to 48+00	0.2244	6.84	1.12×10^{-6}
Survey stations 24+00 to 28+00	0.1270	3.87	6.32×10^{-7}

were freezing temperatures. Heave rate was divided by 1.09 (the expansion of water when frozen) to get an estimate of the water flow rate required to sustain the heave. Estimates of required flow rates were made for two sections at the airport having relatively high and low heave. The results of these estimates are presented in Table 4.

The water flow rates shown in Table 4 indicate the possibility that the hydraulic conductivities of subgrade materials may be a limiting factor in the actual amount of heave. Saturated hydraulic conductivities of 10^{-6} cm/s and less are typical of "impervious" soils such as clays, whereas values of 10^{-4} to 10^{-6} cm/s are characteristic of very fine sand, silts, loams and glacial till (Terzaghi and Peck 1967). Considering the subgrade soil types at the airport, and considering that a large portion of them probably exist in a less than saturated state during most of the winter (i.e., unsaturated hydraulic conductivities are lower than saturated hydraulic conductivities), it seems probable that hydraulic conductivity limits the heave rate, at least during part of the time that heave is occurring.

At Ravalli County Airport, soil horizons with high clay and silt content may not have sufficient capability of transporting water at a rate required to produce significant heave. The hydraulic conductivity of any soil layer depends on water content, and if hydraulic conductivity were limiting the frost heave rate, this would necessitate relatively high water contents so that gravel would remain more permeable than silt, which would be more permeable than clay. This appears to be a reasonable assumption, as the water table does occur in the "gravel" layer along the whole length of the airport, and soil boring logs indicate that this layer contains enough fines to have a relatively high capillarity of 1.5 m (5 ft) or greater. Therefore, it seems likely that the relatively high hydraulic conductivity of gravel could be responsible for

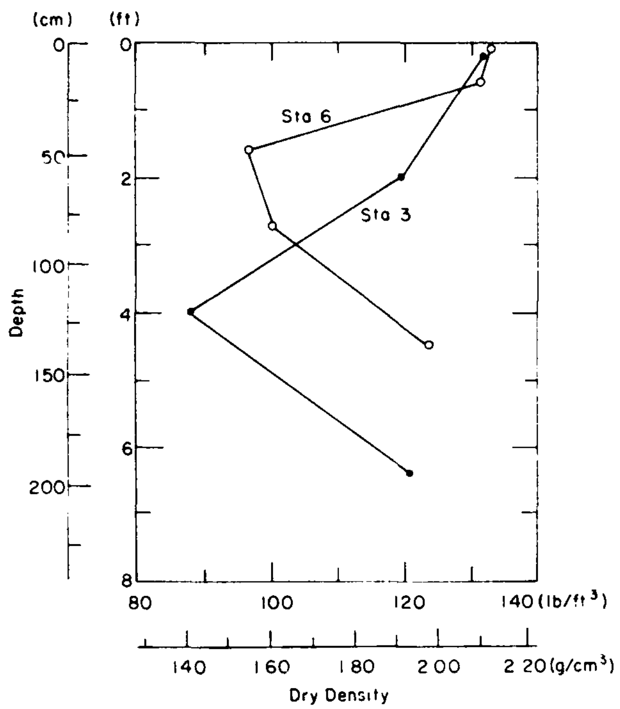


Figure 4. In-situ soil density determinations versus depth at monitoring stations 3 and 6 (6 August 1986).

increased frost heave in the vicinity of station 6, as the gravel layer here appears to be shallower and thicker.

The soils at the low-heaving site (station 3) are denser than those at the high-heaving site (station 6) at depths up to 1 m (3 ft) by about 13% (see Fig. 4). However, when soils in the laboratory frost heave tests were compacted to densities approximating those in the field, no significant difference in heave rates was observed.

Reed et al. (1979) state that for a given soil (silt and clay mixture), samples, compacted so that a relatively large number of large pores remained, heaved at a higher rate than soils compacted to have smaller pore sizes. It is likely that less dense soil in the field would have a greater number of large pores and therefore have higher heave rates. Dense soil would also be likely to have greater effective stress, all other things being equal, and thus would be more resistant to frost heave.

The process of freezing and thawing could cause soil to become less dense. For example, consider a silty subgrade that is compacted to specifications such as to within 90% of optimum density. During the winter, ice lenses form and cause heaving and separation of some of the soil particles. After thawing in the spring, the water may drain away, but the weight of the surcharge (asphalt, base course and any overburden) is not capable of returning the soil to the same density as the original compactive effort (Sayles et al. 1974).

Pavement cracking and pumping of fine particles into the base course during the spring thaw season may be a cause of both decreased soil density and increased frost-susceptibility. This is attributable not only to loss of soil strength and overburden pressure, but also to fine particles being distributed in the base course.

Although less dense soil occurs in the high-heaving area, it is not certain whether it contributes to, is an effect of, or is some combination of cause and effect of, frost heave. It should also be kept in mind that there are only two soil density profiles and the soil type is variable, so that the apparent association of low density soil with high frost heave is somewhat dubious without further testing.

In conclusion, it appears that two soil-related parameters correspond to relative amounts of frost heave—hydraulic conductivity of soils between the water table and the surface and soil density. However, soil density may be an effect or a cause of ice segregation.

WATER AVAILABILITY

As water must be present for frost heave to take place, water availability is considered. Berg and Johnson (1983) provide the guidance that ice segregation can be a problem when the highest groundwater table or perched water table is, at any time of the year, within 152 cm (5 ft) of the subgrade surface or the top of any frost-susceptible subbase materials.

The highest water tables for the 1985–86 season occurred on 4 September 1985. On this date none of the runway stations recorded a water table within 152 cm (5 ft) of the surface of the subbase material; the deepest water table recorded was 265 cm (8.7 ft) at station 7. Taxiway station 2 recorded a water depth of 149 cm (4.9 ft) and station 4 recorded the highest water table at 137 cm (4.5 ft).

Berg and Johnson (1983) say that if the shallowest water table throughout the year is more than 305 cm (10 ft) from the surface of frost-susceptible material, "ice segregation and frost heave *may* be reduced." Since the water table never dropped below 305 cm (10 ft) throughout the year at any monitored station, with the possible exception of station 7, it is reasonable to assume that the entire runway and taxiway have ample water to sustain at least some ice segregation. Please note that this criterion is empirical, and water table depth as an

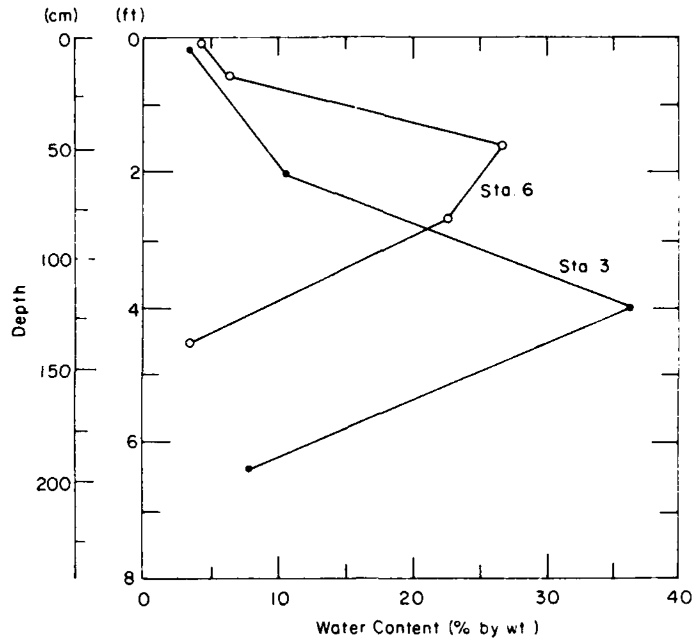


Figure 5. In-situ water content determinations at stations 3 and 6 (6 August 1986).

indicator of frost heave problems will obviously vary with soil type.

In-situ water content determinations made on 6 August 1985 are shown in Figure 5; the average water content by weight for the first 1 m (3 ft) of soil was 8.1% for station 3 and 17.8% for station 6. Silt samples taken from stations 3 and 6 in August of 1985 were saturated, even though the water table was deeper than the horizons from which they were taken. This is indicative of infiltration as a source of water, and possibly high water retention by the soils. Capillarity may contribute to this phenomenon as well. Weather records for the summer of 1985 show that during May through July, total rainfall was less than average at 5.28 cm (2.08 in.), while in August alone there was 6.81 cm (2.68 in.) of rainfall, 4.45 cm (1.75 in.) above the monthly average. Furthermore, Hanson* said that extensive flood irrigation occurs to the east of the airport and he believes that this may increase the water content of the soils at the airport.

The location of highest recorded heave at the airport (16.5 cm [0.54 ft]), survey station 4 on the taxiway, is in the vicinity of the highest water table recorded at all stations on the dates of 4 September, 1 November and 11 December. (Unfortunately, the test hole was silted in on 11 December and no further readings were taken.) Station 2 on the taxiway, reporting the second highest water tables, also heaves considerably—8.5 cm (0.28 ft). Thus, it appears that in these cases the vicinity of the water table is associated with severity of frost heave; however, such a generalization cannot be made for the rest of the airport. For example, severe heave occurred at station 6 (10.7 cm [0.35 ft]), and the water table at this location ranged between 223 and 532 cm (7.3 and 8.8 ft) during the year.

An important aspect of water supply is that of water distribution above the water table. If the soil's "water holding capability" is the same for stations 3 and 6, higher amounts of water present in the subgrade above the water table would probably result in greater frost heave.

High water content during the summer at station 6, compared to that at station 3, *may* reflect initial conditions at the beginning of the freezing season. The higher water content at station 6 could result from a number of factors, including 1) greater porosity (i.e., related to lower density), 2) different soil types with different water holding capacities, 3) greater infiltration rates and 4) greater capillarity. Greater capillarity is not likely to be an important factor in this case since the soils under consideration are so close to the water table surface. Unfortunately, water retention characteristics are unquantifiable with the present information. The

* Personal communication with T. Hanson, Professional Consultants, Inc., Missoula, Montana, 1986.

greater porosity at station 6 compared to station 3 seems likely ascribable to the density differences already discussed. Higher infiltration in this area is also possible.

Water supply to growing ice lenses from water sources below the freezing front is likely to be limited by the hydraulic conductivity of intervening material, as mentioned previously. Thus, although the entire airport has adequate water supply to sustain some frost heave, an argument can be made that the rate of water transport to a growing ice lense strongly depends on hydraulic properties and initial water contents in the vicinity of freezing temperatures.

To summarize, the water table level varies with location throughout the airport. This may affect heave rates—especially in the locations of the highest water table, near station 4 on the taxiway, and the lowest water table, near station 7 on the extreme southern end of the runway. Water supply to the freezing front may also be assisted by water distribution in the soil above the water table as well as the hydraulic properties (i.e., hydraulic conductivity and water holding capacity) of soils between the freezing front and the water table.

CLIMATE

The Bitterroot Valley experiences cool summers and mild winters. The USDA (1959) reports that Hamilton has an average annual temperature of 7.8°C (46.1°F), an average January temperature of −3.7°C (25.4°F) and an average July temperature of 19.9°C (67.8°F). Temperatures below −18°C (0°F) normally occur on fewer than 10 days each winter (USDA 1959). Snowfall and rainfall are relatively light—with precipitation normally ranging from 30.5 to 25.6 cm (12 to 14 in.) annually. Thus, this region may be classified as arid.

The average monthly temperatures based on a 29-year record, and the average monthly temperatures for the 1985–86 winter are presented in Table 5 (NOAA 1984, U.S. Weather Service 1985, 1986). Data are also presented for 1978–79, the coldest winter in the past 15 years. Inspection of this table reveals that in 1985–86, the months of November and December were cooler than average, while January and February were relatively warm. Colder years are expected as evidenced by the temperatures recorded in 1978–79.

The air-freezing index is a quantity used during design to predict frost penetration. It is defined as the number of degree-days between the highest and lowest points on a curve of cumulative degree-days versus time for one freezing season, and it measures the combined duration and magnitude of below-freezing temperatures during any freezing season. The design freezing index is defined as either the air-freezing index for the coldest winter in 15 years, or the average of the two coldest winters in 30 years (Berg and Johnson 1983).

The air-freezing index for 1985–86 was calculated to be 483°C (869°F) based on mean daily temperatures as published by NOAA (1985, 1986). This appears to be near "average" as shown by an isoline map of mean air-freezing indices in North America provided by Berg and Johnson (1983). The design air-freezing index (calculated for the coldest winter in 15 years) was calculated to be 830°C (1494°F). This is 1.7 times the freezing index of 1985–86.

In design practice, the air-freezing index is used to predict maximum depths of frost penetration. Berg and Johnson (1983) give estimates of frost penetration depths for air-freezing indices, dry unit weight and water content of soil. By use of their procedure for 1985–86, and by taking weighted averages of unit weight and water content for the first 1 m (3 ft) of soil, a frost penetration of 120 cm

Table 5. Monthly climatological data for Hamilton, Montana.

	Average mean temperature 1951–1980		*Average mean temperature 1985–1986*		*Average mean temperature 1978–1979 (design year)*		*Average snowfall 1951–1980*	
Month	*(°F)*	*(°C)*	*(°F)*	*(°C)*	*(°F)*	*(°C)*	*(in.)*	*(cm)*
November	34.1	1.17	23.7	−4.58	2	2.8	4.3	10.9
December	28.3	−2.06	18.11	−7.72	18.90	−7.28	9.5	24.1
January	25.0	−3.89	31.5	−0.27	6.6	−14.11	12.5	31.8
February	31.8	−0.11	32.8	0.83	30.41	−0.89	6.2	15.7
March	36.3	2.39			39.7	4.25	8.1	20.6

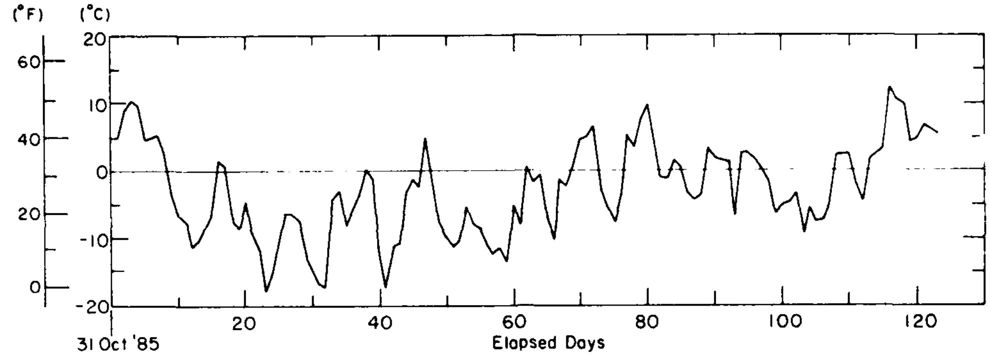


Figure 6. Mean daily surface temperatures, winter 1985–86, Hamilton, Montana.

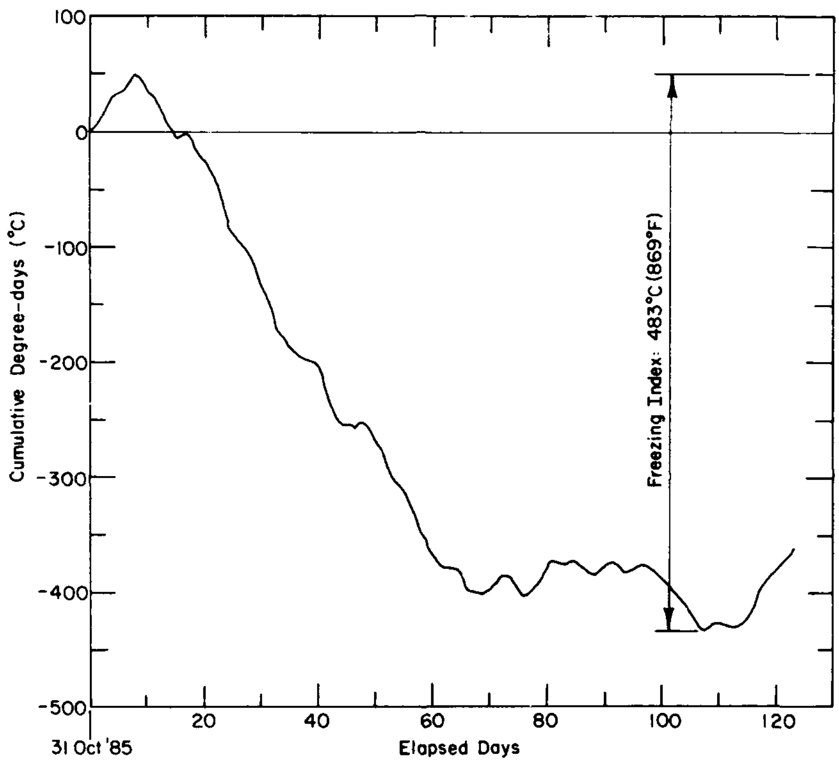


Figure 7. Cumulative degree-days and air-freezing index, winter 1985–86, Hamilton, Montana.

(47 in.) is predicted for station 3 and a frost penetration of 97 cm (38 in.) is predicted for station 6. Actual frost penetration measured at the airport was less than these estimates, but not significantly—the maximum frost depth measured at the airport in January 1986 was 86.4 cm (34 in.) at station 6 (readings were not taken at station 3). Frost penetration predicted with the use of the design freezing index is 142 cm (56 in.), about 30% greater than that predicted with the 1985–86 air-freezing index. Obviously, greater frost penetration and more frost heave can be expected during a more severe winter.

Figure 6 is a plot of the mean daily surface temperatures for Hamilton for the winter of 1985–86 (1 November through 28 February) obtained from NOAA (1985, 1986). Figure 7 presents cumulative degree-days for the same period of time, and shows the air-freezing index for the season.

Figures 6 and 7 show the relatively steady freezing period from 9 November (day 8) through 8 January (day 69), after which a warming trend (above 0°C [32°F]) of 4 days is followed by 4 days of below freezing temperatures. The day that heave was measured by survey, 16 January (day 77), falls at the end of this second freezing period.

PRESENTATION OF MONITORING DATA

Description of equipment

Frost depth measurements were made with "frost tubes" developed at CRREL by Carbee (undated). The tubes consist of an outer cylinder of PVC, an end cap and a clear plastic inner cylinder containing a mixture of water and methyl blue. As the water freezes, methyl blue is expelled and the ice formed is clear. The depth to the clear/blue interface is taken to be the frost depth. The end cap is used to prevent heat loss by surface convection from the frost tube.

Soil moisture tension measurements were made with tensiometers produced for use in the field. Tensiometers are generally very reliable in unfrozen soil, but unreliable in frozen ground.* Two types of tensiometer behavior in frozen soil have been noted. First, as the freezing front passes, the soil moisture tension measured remains high—approximately the same value recorded when the freezing front was present. Second, the soil moisture tension falls once the freezing front passes. It is thought that the readings that remain high are the "more correct" of the two, as this is what happens in the laboratory when tensiometers can be carefully monitored and attended each day.

* Personal communication with J. Ingersoll, CRREL,

Field data

Figure 8 shows depth the to frost front as measured with frost tubes as well as depth to the water table for stations 1, 4 and 6 throughout the winter of 1985–86. Unfortunately, the groundwater monitoring tube for station 4 was silted in on 11 December 1985 and no further readings were taken.

The water table fluctuated within 60 cm (2 ft) for both stations 1 and 6 throughout the winter. For days 1 and 64 the water table and frost penetration depths increased for both stations.

On day 64, at station 1, the frost penetration was 69 cm (2.25 ft), while the water table had dropped by 49 cm (1.6 ft). At station 6, the frost penetration on day 64 was 81 cm (2.67 ft) while the water table had dropped only 15 cm (0.5 ft). Heave of the closest survey station was compared with water table depression. There was no evidence of a general trend towards heave being associated with water table depression. Any trends, however, may have been obscured by, first, the fact that heave measurements were not taken at exact locations of monitoring points and, second, a general lack of data points.

The increase in the water table for stations 3 (Fig. 9) and 6 at the time of measured maximum frost penetration (day 71) is possibly explained by the

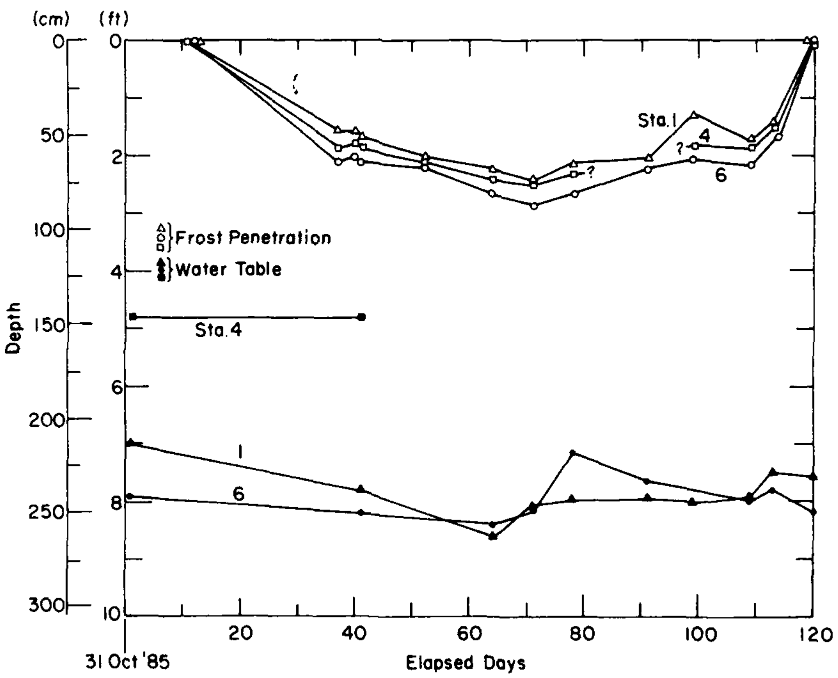


Figure 8. Depth to frost front (frost tube measurements) and depth to water table for stations 1, 4 and 6, winter 1985–86.

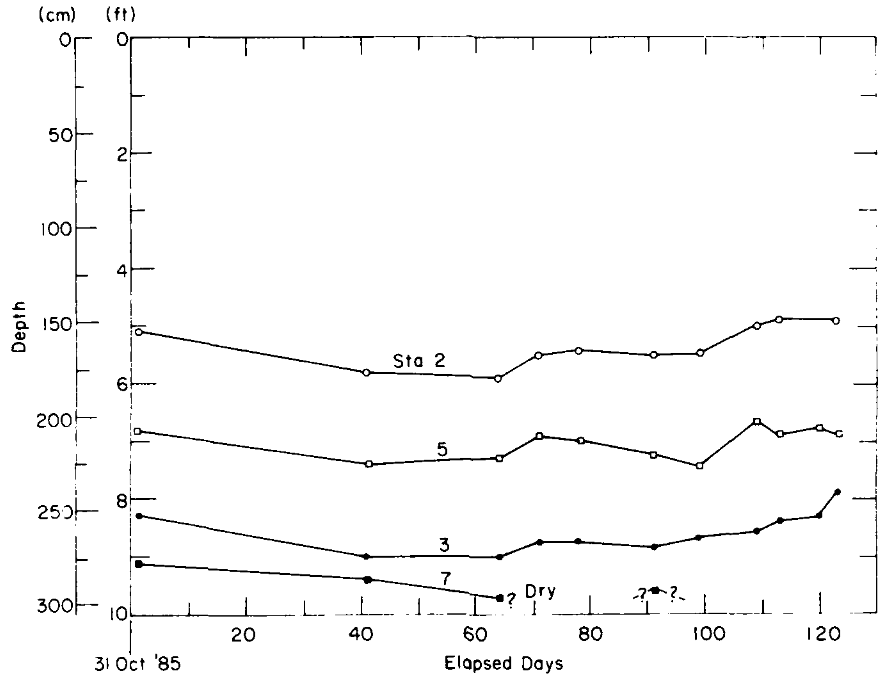


Figure 9. Depth to water table for stations 2, 3, 5 and 7, winter 1985–86.

brief warm period for the 2 days prior to and the day of the measurement. This warm period may have caused melting that released water to the water table. No significant increase in water table height is noted on day 78, which is preceded by only 1 day of warm weather.

Water table depths for stations 2, 3, 5 and 7 (Fig. 9) are similar to the curves for stations 1 and 6—tending to decrease from days 1 through 64 and generally increasing thereafter.

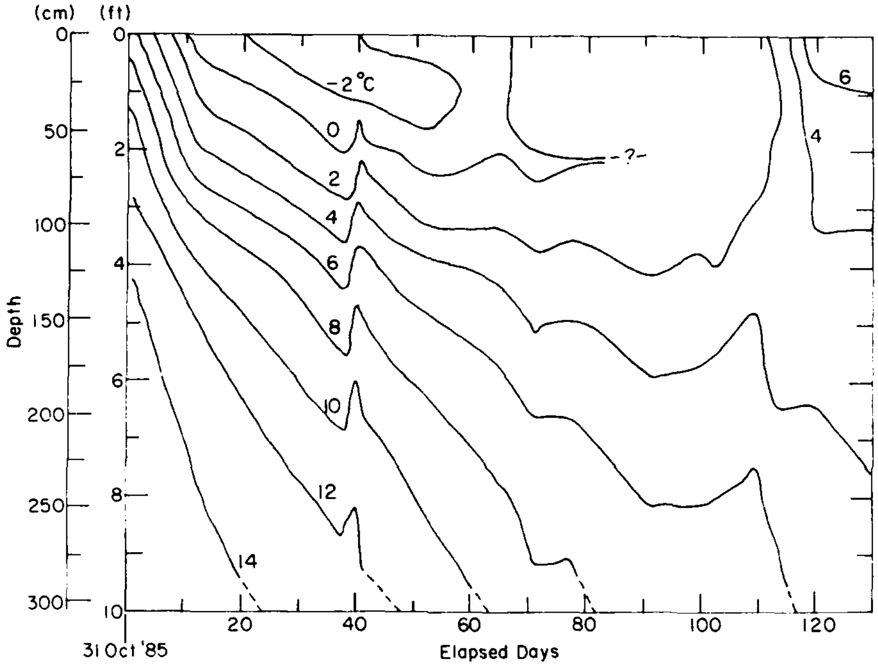
Thermocouple data for stations 3 and 6 are presented in Figure 10. The data are presented in the form of a three-dimensional plot of temperature, time and depth. Frost penetration measured with frost tubes for station 6 indicates a somewhat deeper freezing line than that of the 0°C isotherm. This may be partially caused by relative movement of the thermocouples with respect to the frost tube. Another possibility is that greater heat transfer took place at the surface of the frost tube, causing the water to freeze noticeably deeper than where the 0°C isotherm was located in the ground. A third possibility is that, since the thermocouples were placed directly beneath the pavement, while the frost tubes were not, the pavement surface may be warmer than the adjacent area (because of absorbed short-wave radiation), thus showing a shallower 0°C isotherm.

The thermocouple data show more sensitivity to fluctuations in surface temperatures than do the frost tubes. Frost remains in the ground much longer than the thermocouple data indicate. This may be ascribable to the difference in absorbed radiation noted above. It is possible that freezing temperatures exist "between" thermocouple points, as indicated by the dashed lines in Figure 10.

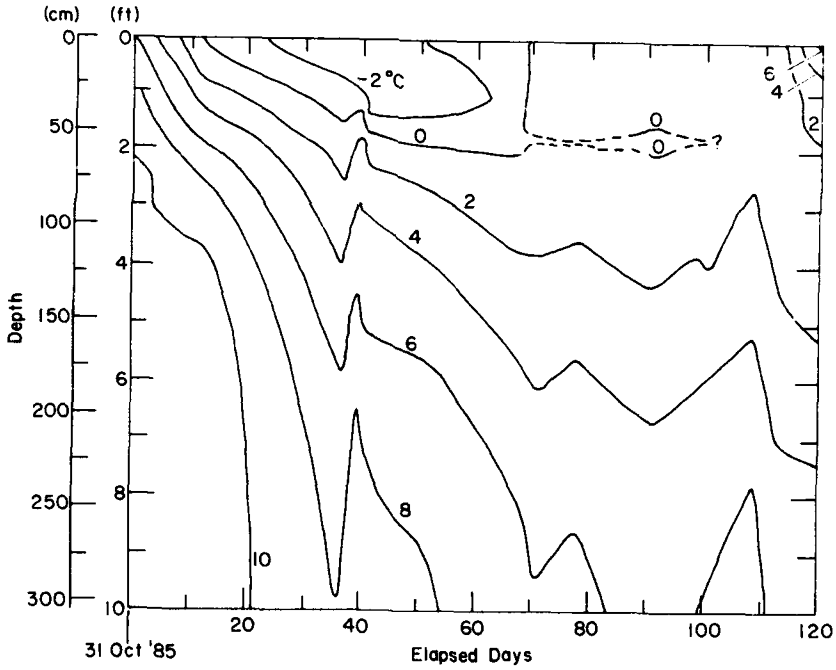
The actual 0°C isotherm in the ground does not coincide with the freezing front and probably is somewhat ahead of it. This is because the soil water, containing impurities, has a depressed freezing point (Hallet 1978). Additionally, any adsorbed water has a lower freezing point than free water. It is noted, however, that the freezing points of soil water in the laboratory frost-susceptibility tests are within 0.07° of 0°C (0.13° of 32°F); this does not necessarily reflect field conditions, only the average freezing points of soil water in the laboratory tests.

The thermocouple data give a measurement of the thermal gradient in the ground and thus allow the estimation of the rate of energy loss from a given volume of soil. It is possible that the rate of energy loss from the soil is a factor limiting the rate of frost heave. Frost penetration will result if heat loss from the soil is greater than heat brought into the soil by water flowing to the freezing front and then freezing (Gold 1985).

Estimates of heat loss rate and the rate of heat input to 1 m^3 (35 ft^3) of soil were made and the two quantities were compared. The results are presented in Table 6. Many assumptions had to be made to do these calculations, and they are listed in



a. Monitoring station 3.



b. Monitoring station 6.

Figure 10. Soil temperature variation with depth and time, winter 1985–86.

Appendix B along with all the data used, a description of the procedure followed and a sample calculation. The most important assumption was that the rate of water flow to the freezing front was constant throughout the winter and equal to the rate required to sustain the frost heave measured on 16 January, assuming that heave began on 12 November.

Table 6 reveals that, in the beginning of the freezing season, the ratios of heat loss rate to rate of heat input for stations 3 and 6 are relatively high and approximately the same. As the freezing sea-

Table 6. Estimated rates of heat loss to rate of heat input for soil near freezing front at monitoring stations 3 and 6, Ravalli County Airport.

Date	*Estimated depth of frost penetration (ft)*	*(cm)*	*Station 3*	*Station 6*
12 November	0	0	7.7	7.2
24 November	1.0	30.5	6.1	8.3
7 December	2.1	64	5.7	2.9
10 January	2.8	85	4.6	1.4

son progressed, however, the ratio of heat loss rate to rate of heat input at station 6 became significantly smaller than that for station 3. This indicates better ice lens growth conditions at station 6.

The difference in heat loss/heat input ratios between the two stations are related primarily to the differences in thermal gradients and the flow rate of water to the freezing front assumed; the differences in thermal conductivities assumed are not large. Since station 3 had a significantly lower assumed rate of water flow to the frost front, this would tend to result in higher ratios of heat loss rate to heat input rate. However, the thermal gradients at station 3 were lower than those at station 6 in the early season, but higher later in the season. For both stations the thermal gradients were relatively high early in the season when most of the frost penetration occurred. It is therefore reasonable to assume that most of the frost heave occurred after early December, when the rate of heat loss from station 3 was notably higher than the rate of heat loss from station 6.

The differences in frost heave observed at stations 3 and 6 at Ravalli County Airport appear to be influenced by the rate of heat loss from the ground as well as the hydraulic conductivity of the material between the water table and the freezing front, as previously discussed. Heat loss rate versus rate of heat input can be limited by the rate of water flow (Gold 1985). There is no obvious explanation why the rate of heat loss from station 3 is greater than that at station 6 late in the freezing season, except for the possibility of limited water flow. The airport is flat and very open, so conditions at the surface would be nearly the same. The water content of soils near the freezing front would be important, as water has a very high capacity to store and transport heat; I don't have enough information regarding the field conditions to comment further.

Soil moisture tension data are presented in the same manner as soil temperature information (Fig. 11).

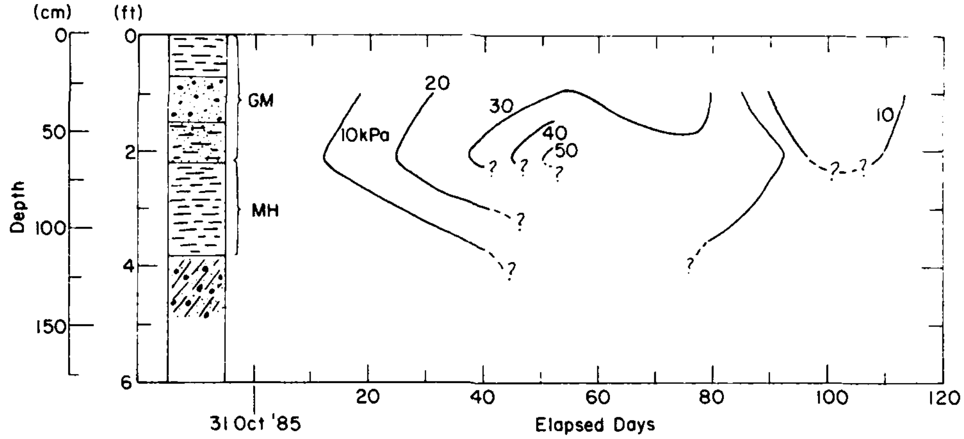
On Figure 11a, the tensiometer readings at the depth of 112 cm (3.67 ft) are 0.0 for the entire season after day 41. These values are suspect because of their constancy with time and because they indicate saturated (or near saturated) conditions. The groundwater table is measured at depths ranging from 244 to 274 cm (8.0 to 9.0 ft) for the entire freezing season and earlier readings indicate significant tension at 112 cm (3.67 ft). Therefore, it is likely that the reading of 0.0 is incorrect. A reading of 0.0 at a depth of 44 cm (1.45 ft) is also unlikely to be accurate for the same reasons. Hanson* recorded these values and recalls having difficulty with the tensiometers beginning in mid-January. The tensiometers may have been broken by freezing or frost heaving; thus, the contours were omitted from the appropriate regions in Figure 11b.

Figure 11b shows high tensions (30–40 kPa) existing near the freezing front, especially from days 38 through 71 when the frost penetration rate had leveled off compared to the beginning of the freezing season. This behavior is as expected since relatively high freezing rates in the beginning of the season would probably not permit the development of high tension. The actual tension was probably higher than the measurements indicated because of the length of time between readings. Past work has shown that very steep moisture tension gradients exist near the freezing front; the actual value of moisture tensions at the freezing front can be 70 kPa or higher.†

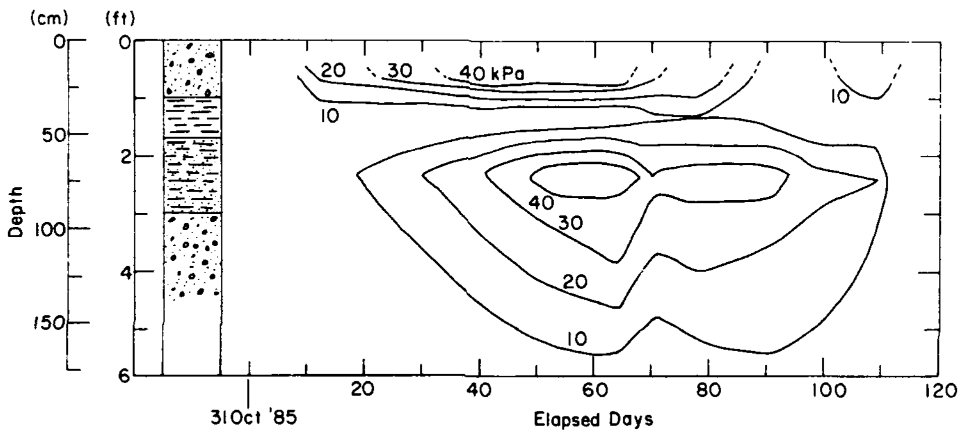
Based on the results shown in Figure 12, hydraulic conductivities of soils near the freezing front (experiencing soil moisture tensions of 40–70 kPa) are on the order of magnitude 10^{-7} cm/s. When this flow rate is compared with estimated flow rates required for frost heave (see Table 4), it becomes apparent that they possibly limit the rate of heave. (In the *Frost Heave and Soil Type* section, it was determined that the hydraulic conductivities of a larger portion of the soil, below the freezing front, may also be limiting frost heave rates.) Note that the estimate of heave rate was based on only one frost heave measurement, so these conclusions should still be considered tentative. More frequent measurements of both heave and soil moisture

* Personal communication with T. Hanson, Professional Consultants, Inc., Missoula, Montana, 1986.

† Personal communication with E. Chamberlain, CRREL, 1986.



a. Monitoring station 3.



b. Monitoring station 6.

Figure 11. Soil moisture tension variation with depth and time, winter 1985–86.

tension would have allowed for a more accurate determination of the contribution of limits on water flow rate to frost heave rate.

Figure 11a shows that during the frost penetration period, soil moisture tension gradually falls off above the freezing front, while Figure 11b shows soil moisture tension rapidly falling off, then increasing towards the surface. The trend shown in Figure 11b could be caused if only one tensiometer (placed at the 40-cm [1.3-ft] depth) gave incorrect readings after the passing of the freezing front. As mentioned earlier, tensiometer readings in frozen soil are not well understood, and readings above the freezing front were therefore not considered.

In summary, thermocouple data allowed an estimation of rates of heat loss and these were compared with heat input rates. The comparison revealed a much higher heat-loss-rate-to-rate-of-heat-input ratio for a low heaving site than a high heaving site during the part of the freezing season when most of the frost heave occurred. This was primarily a function of both the thermal gradients and water flow rates. The tensiometers show increasing soil moisture tension in the vicinity of the freezing front, as expected; however, readings in frozen soil are unreliable. Furthermore, the maximum tensions reached were likely to be higher than those recorded, and the unsaturated hydraulic conductivity of soils near the freezing front at station 6 may possibly limit water flow to ice lenses.

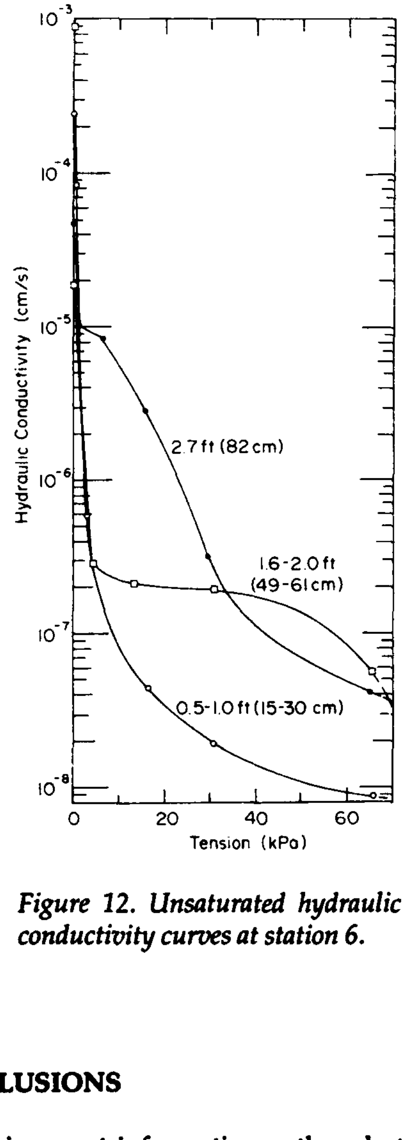


Figure 12. Unsaturated hydraulic conductivity curves at station 6.

CONCLUSIONS

In this report information gathered at Ravalli County Airport was presented and analyzed in terms of the three factors necessary for frost heave—frost-susceptible soil, water availability and freezing temperatures. The study focused on two areas on the runway—survey stations 26+00 (station 3) and 43+50 (station 6), low-heaving and high-heaving sites respectively.

With regard to soil frost-susceptibility, preliminary study revealed that all soil at the airport at depths of 1 m (3 ft) or less should be considered highly frost-susceptible. Testing also revealed the tendency of base course "gravels" (classified according to the Unified Classification System as silty sand) to be somewhat frost-susceptible. Furthermore, there is no clear tendency for either base course or subgrade soils to differ in frost-susceptibility between stations 3 and 6. Low density soil was noted in the vicinity of station 6, but whether it is a cause, effect or both cause and effect of frost heave is uncertain.

There is a strong possibility that saturated hydraulic conductivities of subgrade materials near the water table at Ravalli County Airport limit frost heave. Specifically, it is likely that the relatively large hydraulic conductivity of a shallow gravel layer near the southern end of the airport allows the water flow required to sustain large amounts of frost heave.

Water availability probably affected rates of heave at the airport. In addition to the hydraulic conductivity differences already noted, station 6 had significantly higher in-situ water content than station 3 in the depth of soil likely to be penetrated by freezing temperatures. Minimum depths to the water table (less than 1.52 m [5 ft]) occurred in areas of very high heave and maximum depth of water table (greater than 3.05 m [10 ft]) in areas of low heave. Between these extremes no consistent trends of heave versus depth of the water table were noted. According to empirical criteria prescribed by Berg and Johnson (1983), it is likely that the entire airport has adequate water supply to sustain considerable heave, with the possible exception of survey station 48+00 on the runway.

The winter of 1985–86 was not exceptionally cold and frost penetration during a severe winter may be expected to be about 30% greater, with an unknown increase in frost heave.

Soil temperature data at stations 3 and 6 allowed the determination of thermal gradients in the vicinity of the freezing zone at various times throughout the season. This led to the estimation of heat loss rate by the use of Fourier's Law. The rate of incoming heat was approximated based on estimates of water flow to the freezing front. Comparisons of estimated rates of heat loss to incoming heat revealed that this ratio was significantly lower for station 6 than station 3 during the period that most of the heave was likely to be happening. This is a result of differences in the assumed water flow rate and the thermal gradients in the soil at that time. Tensiometer data, which revealed high moisture tensions near the freezing front, indicate that unsaturated hydraulic conductivities in the vicinity of the freezing zone may sometimes limit frost heave by limiting water flow.

Based on the results of the field analysis summarized in this report, and the laboratory study reported elsewhere (Henry, in press), the following design alternatives are suggested to improve the frost heave behavior at Ravalli County Airport.

1. Results of the laboratory tests suggested that a polypropylene fiber geotextile may considerably

reduce frost heave if properly selected to minimize fabric contamination and placed in the silty subgrade. Since this has not yet been tested in the field, a test section could be built under a noncritical pavement section at Ravalli County Airport with a polypropylene geotextile in the subgrade instead of at the subgrade/base course interface. Another test section could be constructed where geotextiles are placed both in the subgrade and between the subgrade and base course. The geotextile should be placed above the water table and at a depth greater than at least 50% of maximum probable frost penetration. At Ravalli County Airport, this would be at about 91–122 cm (3–4 ft).

2. The base course "gravel" should be removed and replaced with a clean gravel containing less than 3% of particles finer than 0.02 mm.

3. The subgrade soil should be removed to a depth of 145 cm (4.75 ft), the depth of maximum probable frost penetration, remixed and compacted into place to achieve more uniform frost heave. Compaction should be as close to optimum as is practical.

4. A properly designed filter fabric should be placed between the subgrade and the base course gravel to act as a separator. If a nonwoven polypropylene geotextile (or a geotextile composed of fibers that have similar surface properties to polypropylene regarding affinity for water) is chosen, it will probably help reduce frost heave, too.

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APPENDIX A: BORING LOGS AND GRAIN SIZE DISTRIBUTION CURVES OF RAVALLI COUNTY AIRPORT SOILS

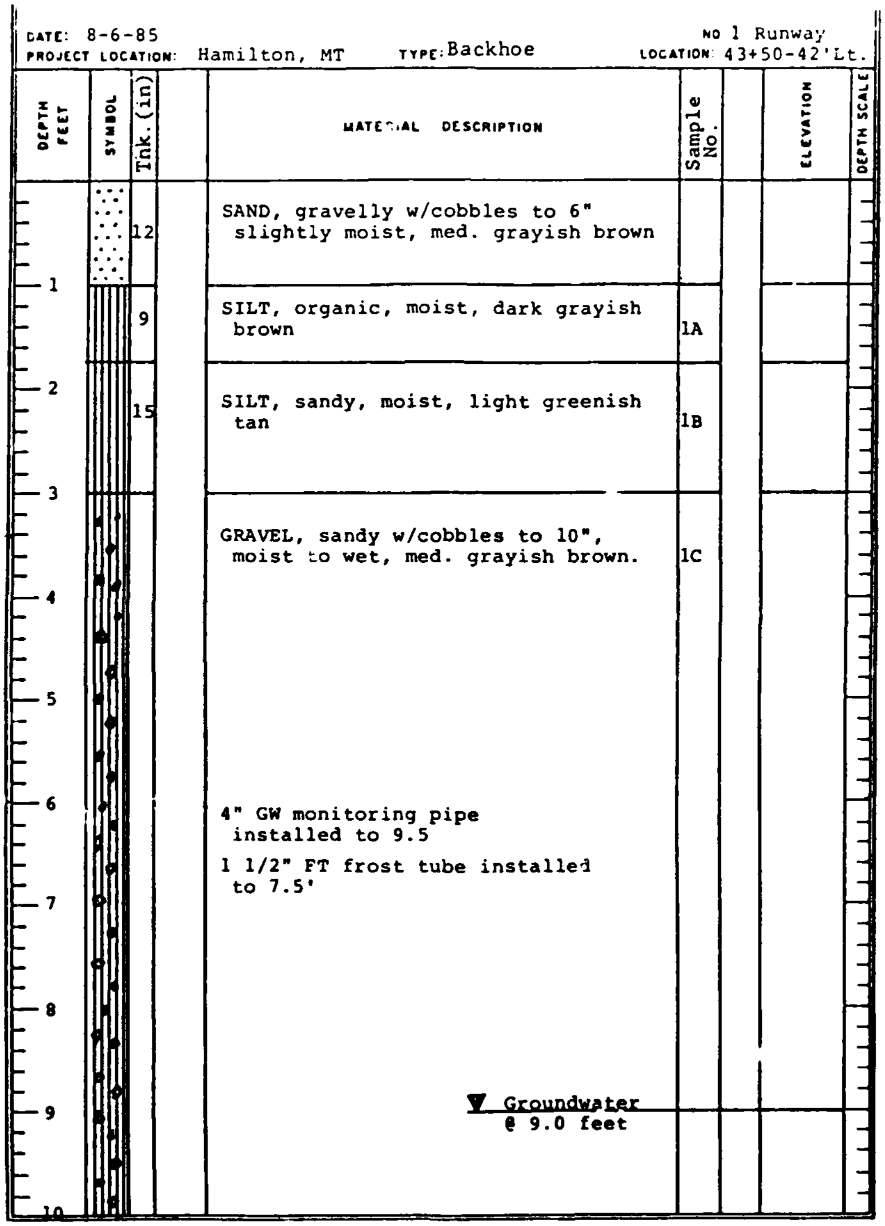

Figure A1. Soil boring logs from Ravalli County Airport.

DATE: 8-6-85
PROJECT LOCATION: Hamilton, MT TYPE: Backhoe
NO 2 Runway
LOCATION 46+00-42'Lt.

DEPTH FEET	SYMBOL	Thk. (in)		MATERIAL DESCRIPTION	Sample No.		ELEVATION	DEPTH SCALE
0–0.7		8		SAND, gravelly w/cobbles to 6", sli. moist, med. grayish tan				
0.7–1.8		13		SILT, slightly organic, moist, med. grayish brown	2A			
1.8–2.3		6		SILT, sandy, moist, tan	2B			
2.3–10				GRAVEL, sandy w/cobbles to 10", moist to wet, med. grayish brown	2C			
8				Groundwater @ 8.0 feet				

Figure A1 (cont'd). Soil boring logs from Ravalli County Airport.

DATE: 8-6-85
PROJECT LOCATION: Hamilton, MT TYPE: Backhoe
NO 3 Runway
LOCATION 48+00-42'Lt.

DEPTH FEET	SYMBOL	Thk. (in)		MATERIAL DESCRIPTION	Sample No.		ELEVATION	DEPTH SCALE
		9		SILT, sli. gravelly, sli. moist, med. grayish brown				
1		9		SILT, organic, sli. moist, dark grayish brown	3A			
2		14		SILT, sandy, sli. moist, tan	3B			
3 4 5 6 7 8 9 10				GRAVEL, sandy w/cobbles to 10" moist to wet, med. grayish brown 4" GW monitoring pipe installed to 9.5 feet 3" BM Benchmark installed to 9.5 feet ▼ Groundwater @ 7.5 feet	3C			

Figure A1 (cont'd).

DATE: 8-6-85 NO 4-Taxiway

PROJECT LOCATION: Hamilton, MT TYPE: Backhoe LOCATION 30+50-20'Lt.

Tnk. (in)	MATERIAL DESCRIPTION	Sample No.
6	TOPSOIL, sandy w/gravel, dry, tan	
6	GRAVEL, silty to sandy, sli. moist med. reddish brown	
3	TOPSOIL, organic, silty, moist, dk.gray	
15	SAND, silty, moist, dark grayish brown	4A
16	SAND, silty, moist to wet, dark grayish brown	4B
	GRAVEL, silty to sandy, wet, iron stained, dark reddish brown ▼ Groundwater @ 5.5 feet 4" GW monitoring pipe installed to 9.5 feet 3" BM Benchmark installed to 8.5 feet 1 1/2" FT Frost tube installed to 6.0 feet.	4C

Figure A1 (cont'd). Soil boring logs from Ravalli County Airport.

DATE: 8-6-85 NO 5-Runway

PROJECT LOCATION: Hamilton, MT TYPE: Backhoe LOCATION. 30+50-42'Lt.

DEPTH FEET	SYMBOL	Tnk. (in)		MATERIAL DESCRIPTION	Sample No.		ELEVATION	DEPTH SCALE
1		20		SILT, organic, w/some gravel and sand, sli. moist, dark gray				
2 3		26		SILT, sli. organic, moist, dark gray	5A			
4		5		GRAVEL, clayey, wet, med. brown				
5		9		SILT, clayey, wet, yellowish brown	5B			
6 7 8		34		GRAVEL, sandy w/cobbles, wet to saturated, med. brown ▼ Groundwater @ 6.8 feet				

Figure A1 (cont'd).

DATE: 8-6-85 NO 6-Runway

PROJECT LOCATION: Hamilton, MT TYPE: Backhoe LOCATION: 40+00-42'Lt.

DEPTH FEET	SYMBOL	Thk. (in)		MATERIAL DESCRIPTION	Sample No.		ELEVATION	DEPTH SCALE
1		17		SILT, gravelly, sli. organic, sli. moist, dark gray				
2, 3		26		SILT, sli. organic, sli. moist, dark gray				
4, 5		21		SILT, sandy, moist, yellowish tan.				
6		14		GRAVEL, sandy, with cobbles, wet, med. brown ▽ Groundwater @ 6.5 feet				

Figure A1 (cont'd). Soil boring logs from Ravalli County Airport.

DATE: 8-6-85
PROJECT LOCATION: Hamilton, MT TYPE: Backhoe NO 7-Runway
LOCATION 36+00-42'Lt.

Thk. (in)	MATERIAL DESCRIPTION	Sample No.	ELEVATION
14	GRAVEL, silty to sandy, dry, med. grayish brown		
22	SILT, organic, sli. moist, dark gray		
14	SILT, clayey, moist, med. grayish tan		
6	GRAVEL, clayey, dark grayish brown		
	GRAVEL, sandy to silty w/cobbles to 10", wet, med. grayish brown ▼ Groundwater @ 6.3 feet 4" GW Monitoring pipe installed to 9.5 feet		

DEPTH FEET: 1, 2, 3, 4, 5, 6, 7, 8, 9

Figure A1 (cont'd).

DATE: 8-7-85
PROJECT LOCATION: Hamilton, MT TYPE: Backhoe NO. 8-Runway
LOCATION: 26+00-42'Lt.

DEPTH FEET	SYMBOL	Thk. (in)		MATERIAL DESCRIPTION	Sample No.		ELEVATION	DEPTH SCALE
		7		TOPSOIL, gravelly to silty, dry, med. grayish brown				
1		10		GRAVEL, w/some cobbles to 6", sandy to sli. silty, dry, med. grayish brown				
		4		SILT, gravelly to sandy, dry, med. gray				
2		5		SILT, gravelly, dry, med. grayish green				
3		20		SILT, organic, moist, dark gray	8A			
4, 5		20		GRAVEL, clayey, gravelly, moist, medium greenish tan	8B			
6, 7, 8, 9, 10				GRAVEL, sandy, wet, medium brownish gray. 4" GW Monitoring pipe installed to 9.5 feet 3" BM Benchmark installed to 9.5 feet ▼ Groundwater @ 9.0 feet				

Figure A1 (cont'd). Soil boring logs from Ravalli County Airport.

DATE: 8-7-85
PROJECT LOCATION: Hamilton, MT TYPE: Backhoe NO 9-runway
LOCATION 17+00-42'Lt.

DEPTH FEET	SYMBOL	Thk. (in)		MATERIAL DESCRIPTION	Sample No.		ELEVATION	DEPTH SCALE
		10		TOPSOIL, silty to gravelly, dry, med. grayish brown				
1		10		GRAVEL, silty to sandy w/cobbles to 6", dry, light grayish tan				
2		18		SAND w/gravel, silty, moist, dark grayish brown	9A			
3–7		46		SAND, silty, "brackish" odor, moist to wet, dark brownish gray.	9B			
7		10		SILT, sandy, wet, med. grayish green	9C			
8–10				GRAVEL, sandy, saturated, med. brown ▼ Groundwater @ 8.3 feet 4" GW Monitoring pipe installed to 9.5 feet 1 1/2" FT Frost tube installed to 6.5 feet				

Figure A1 (cont'd).

DATE: 8-7-85 NO 10-Taxiway
PROJECT LOCATION: Hamilton, MT TYPE: Backhoe LOCATION: 20+00-20'Rt.

DEPTH FEET	SYMBOL	Thk. (in)	MATERIAL DESCRIPTION	Sample No.		ELEVATION	DEPTH SCALE
		9	TOPSOIL, silty to gravelly, dry, med. brownish gray.				
1		7	GRAVEL, silty to sandy, sli. moist, med. grayish brown				
2		18	SAND, silty, moist dark brownish gray	10A			
3		5	SAND, silty, wet, dark grayish brown	10B			
4		9	SAND, silty, wet, medium greenish gray	10C			
5		23	GRAVEL, clayey w/some cobbles, wet, medium orange to greenish tan				
6, 7, 8, 9, 10			▼ Groundwater @ 6.0 feet GRAVEL, sandy w/cobbles, med. grayish tan 4" GW Monitoring pipe installed to 9.5 feet				

Figure A1 (cont'd). Soil boring logs from Ravalli County Airport.

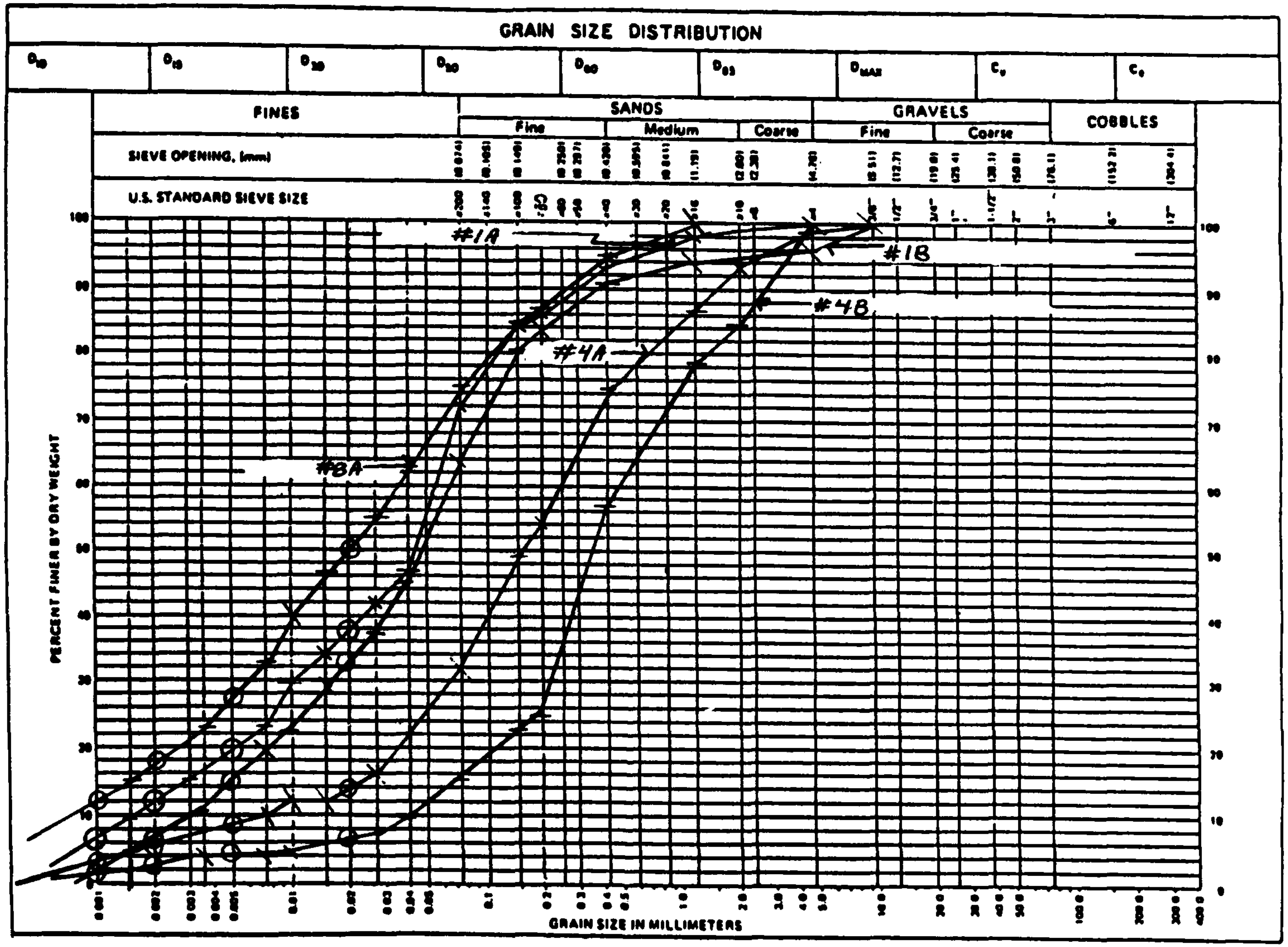

Figure A2. Grain size distributions for soil profile samples (numbers correspond to soil horizons in Figure A1).

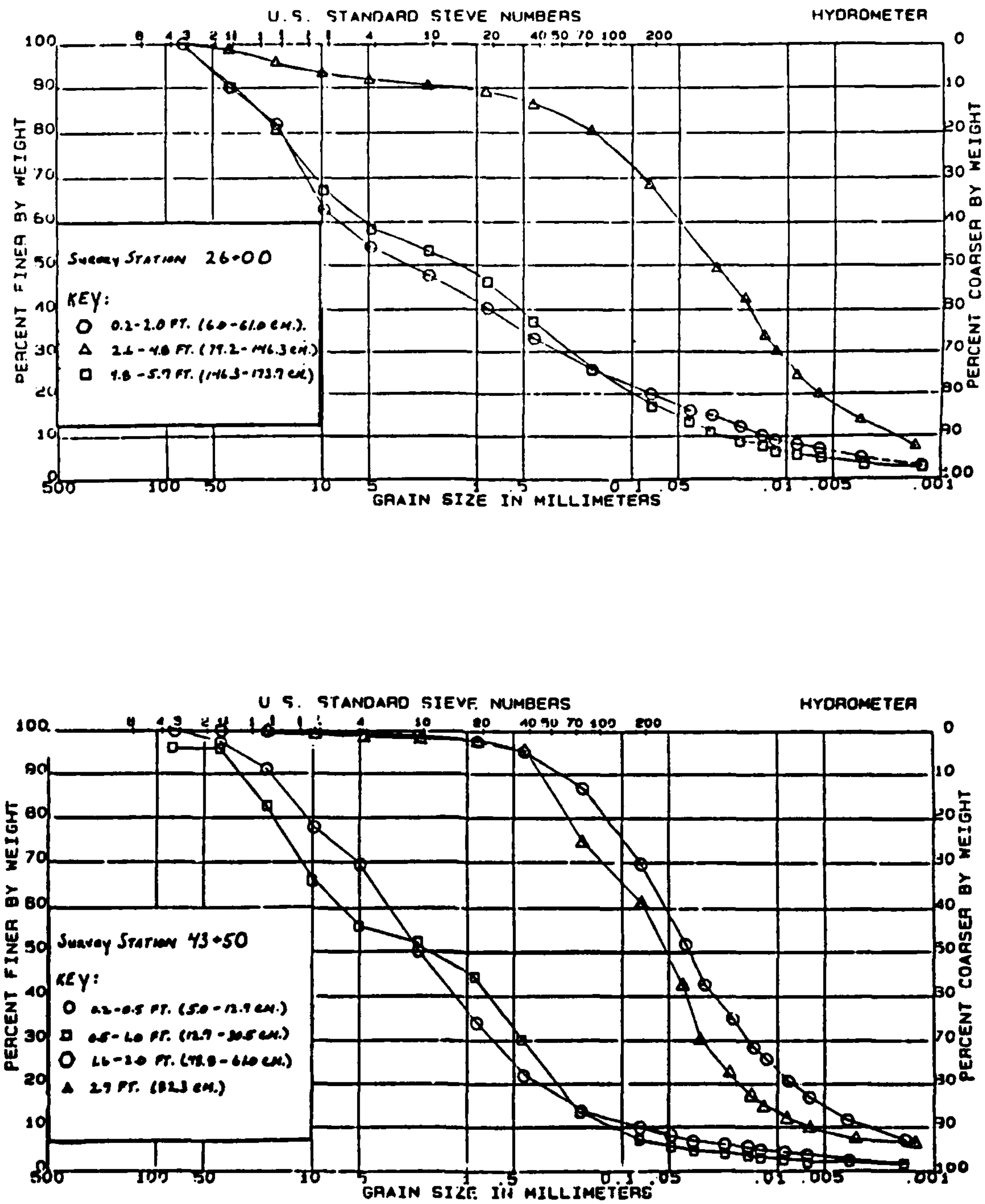

Figure A3. Grain size distributions determined by the CRREL soils laboratory.

APPENDIX B: SOLUTION TO SOIL HEAT TRANSFER PROBLEM

Objective

The objective here is to determine whether heat loss rate was more likely to limit rate of frost heave at station 3, a low heaving site, than station 6, a high heaving site.

Approach

An energy balance was conducted on a 1-m^3 (35-ft^3) volume of soil near the freezing front at several dates throughout the winter. Heat loss from the soil volume was compared to heat added by incoming water and the freezing of that water.

Assumptions

1. There was no water flowing *through* the system.
2. There was no convective heat transfer.
3. Heat transfer was one-dimensional in the vertical direction.
4. Rate of mass flow of water to the soil volumes was constant throughout the winter and estimated by average heave measured on 16 January 1986 divided by 65 days (time between 12 November, assumed onset of soil freezing, and 16 January). The average flow rate used for station 6 (located at 53+50) considered heave at survey stations 41+00 through 48+00, and the average flow rate used for station 3 (located at 26+00) considered heave for stations 24+00 through 28+00.
5. Thermal conductivity of soil, *k*, is accurately estimated by empirically based curves presented in TM-5-852-6 (U.S.Army 1966). An average thermal conductivity for unfrozen and frozen soil is adequate. Furthermore, the estimates based on in-situ dry densities and water contents measured on 6 August 1985 are sufficient. Thermal conductivity of the soil located at the freezing front is preferable to averaging it with the thermal conductivity of soil above the freezing front.
6. The thermal gradient in the vicinity of the freezing front was assumed adequate for these calculations.
7. Frost penetration was the same at both stations and equal to that shown by frost tube measurements made at station 6.
8. All water added to the soil volume is frozen.

Data used

1. *cp*, specific heat of water at 273.15 K = 4217 J/kg K (see Table B1 for English conversions).
2. *l*, latent heat of fusion of water = 3.33×10^5 J/kg.
3. Thermal conductivities of soils (from TM-5-852-6 [U.S. Army 1966])

	Depth (*cm*)	(*ft*)	k (*W/m K*)
station 3	6.1	0.2	2.6
	30.5	1.0	3.0
	64.0	2.1	1.7
	85.0	2.8	1.6
station 6	6.1	0.2	1.7
	30.5	1.0	1.7
	64.0	2.1	1.6
	85.0	2.8	1.6

4. Mass flow rate of water to 1 m^3 of soil at station 3

0.632×10^{-5} kg/s

Mass flow rate of water to 1 m^3 of soil at station 6

1.12×10^{-5} kg/s

5. Average thermal gradients (obtained from Fig. 10)

Date	*Depth of frost penetration (ft)*	*(cm)*	*Thermal gradient, $\Delta T/\Delta y$ (°C/m) station 3*	*station 6*
12 November	0.0	0.0	10.1	11.9
24 November	1.0	30.5	7.7	11.9
7 December	2.1	64	8.2	6.6
10 January	2.8	85	5.7	3.4

Calculations

Heat loss rate from the soil was calculated by Fourier's Law

$$q_o = kA\,\Delta T/\Delta y$$

where q_o = heat loss rate (W)
k = thermal conductivity (W/m K)
A = cross-sectional area perpendicular to heat flow (m)
$\Delta T/\Delta y$ = thermal gradient (K/m)

Heat added to the soil was calculated by the following equation:

$$q_i = \dot{m}\, c_p\, (\Delta T/\Delta y) + \dot{m}\, (l)$$

where q_i = rate of heat added to the soil (W)
$\dot{m}$ = mass flow rate of water to the soil volume (kg/s)
c_p = specific heat of water (J/kg K)
l = latent heat of fusion (J/kg).

Sample calculation

On November 24 the frost penetration was approximately 30.5 cm (1 ft). At this depth on this day at station 3, $\Delta T/\Delta y \cong 8.2$ K/m and $k \cong 1.6$ W/m K. Therefore

$$q_o = 1.6 \text{ W/m K } (1 \text{ m}^2)\,(8.2 \text{ K/m}) = 13.12 \text{ W}$$

$$q_i = 6.32 \times 10^{-6} \text{ kg/s } (4217 \text{ J/kg K})\,(1.6 \text{ W/m K})$$

$$+ 6.21 \times 10^{-6} \text{ kg/s } [3.33 \times 10^{-5} \text{ (J/kg)}] = 2.15 \text{ W}.$$

$$q_o/q_i = 13.12/2.15 = 6.1.$$

Table B1. Conversion factors.

Specific heat:	1 J/kg K = 2.3886×10^{-4} Btu/lbm °F
Latent heat:	1 J/kg = 4.2995×10^{-4} Btu/lbm
Thermal conductivity:	1 W/m K = 0.57782 Btu/hr ft °F
Mass flow rate:	1 kg/s = 7936.6 lbm/hr
Thermal gradient:	1°C/m = 0.16934°F/ft

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Frost action beneath pavements can lead to several problems, including thaw weakening, which causes cracking and subsequent pumping of fine soil particles onto the surface, as well as hazardous conditions caused by differential heaving. This study examined data and frost-susceptible soil collected during the winter of 1985–86 at Ravalli County Airport, Hamilton, Montana, to determine potential causes of frost heave. Variables analyzed were depth to water table, depth of frost penetration, maximum frost heave and soil moisture tension and soil temperature with depth. Analysis of the field data revealed the possibility that hydraulic conductivity of subgrade soils and rates of heat loss in the soil may be limiting frost heave rates. Soil density and depth to water table may also be factors affecting amounts of frost heave. Furthermore, the base course "gravel" used at the airport contained considerable amounts of fines and did heave somewhat in laboratory tests. Recommendations for design changes to reduce frost heave at Ravalli County Airport were made.

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